Performance Evaluation on Resource Allocation with Carrier Aggregation in LTE Cellular Networks

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***Abstract*—Because of a significant increase in heterogeneous user demands, carrier aggregation has been widely proposed to provide higher data rates. Due to a variety of carrier aggregation implementations, the question is what the efficient resource allocation with carrier aggregation could be. Therefore, in this paper, a homogeneous cellular network is modelled using a system-level simulation of the downlink. The resource allocation, including component carrier selection and resource block scheduling, is investigated under different carrier aggregation types and operating frequency bands. The performance is then evaluated in terms of user throughput. By using the proper combination of carrier selection and scheduling, not only can the load across all carriers be balanced but also higher throughput is obtained. However, the use of resource allocation with carrier aggregation should be adapted since there is a trade-off of user performance and implementation complexity.**

***Index Terms*—Long term evolution (LTE), carrier aggregation, scheduling, system-level simulation**

I. Introduction

Due to an exponential growth of mobile devices and bandwidth demands in wireless networks, cellular networks need to offer higher data rate for a variety of users and applications. The use of wider bandwidth is an explicit solution. However, the available resource appears to be non-continuous with different bandwidths and frequency bands because of regional regulation. This results in carrier aggregation (CA) launched by the 3rd Generation Partnership Project (3GPP) under long term evolution advanced (LTE-A) standards. To produce the wider bandwidth, two or more component carriers (CCs) with different bandwidths and bands can be combined.

According to [1], there are three types of CA including intra-band contiguous, intra-band non-contiguous and inter-band non-contiguous. Because of physical layer and hardware design, the choice of CA implementation should be adapted. Moreover, the operation of resource allocation with CA can be extended. The set of CCs is first assigned to each user equipment (UE) by the base station (eNB). Then, resource block(s) (RB) will be allocated to scheduled UE(s) on each CC. These two main tasks are known as CC selection and RB scheduling.

Recent works on resource allocation with CA may be divided into two classes: separate and joint resource (CC and RB) allocation problems. In [2], [3], the CC selection and RB scheduling are performed independently. A group of CCs is likely selected by using random, round-robin (RR) and reference signal received power (RSRP) methods. This selection is restricted from the CA capability of the UE. For the RB scheduling, RR, best-channel quality indicator (CQI) and proportional fair (PF) techniques can be used.

Another option is the joint CC selection and RB scheduling. For example, a non-linear integer programming problem is formulated for such a joint resource allocation in [4]. Because of the computational complexity, the PF scheduler is first performed on each CC. Subsequently, an iterative algorithm called, minimising system utility loss (MSUL), is applied to meet the CA capability constraint of UEs. This sub-optimal algorithm aims to maximise the network utility function.

According to [5], the modulation and coding scheme (MCS) constraint is included in the joint problem. At each subframe, the largest utility function is calculated by a greedy algorithm (GA) from all combinations of UEs, CCs and MCSs. RB(s) is then assigned as regards the weighted data rate of UE. In [6], the MSUL is modified to support MCS assignment as well.

The primary CC (PCC) and secondary CC (SCC) selection have also been considered. An integer linear programming problem with RB, MCS and SCC constraints is formulated in [7], [8]. By using the linear programming relaxation, this problem can be optimally solved.

Although the network performance could be enhanced by the joint resource allocation, the higher computational complexity is required as compared with the separate approach. Therefore, a compromise between complexity and performance should be considered carefully in practice.

This paper aims to model the resource allocation with CA for a downlink (DL) LTE cellular network by means of system-level simulation, in particular separate CC selection and RB scheduling. As compared with [2], [3], a wider variety of CA scenarios is considered in this article. The UE throughput will be evaluated in connection with different CA types, CC selection, frequency bands and scheduling. For example, the 3.4 GHz spectrum is investigated[1]. Thus, a comprehensive study of CA implementation could be provided through this work.

[1]The 3.4 GHz band refers to the potential spectrum from 3410 - 3600 MHz used for mobile broadband and fifth generation (5G) services in the UK [9].

The remaining sections are organised as follows: the system model is discussed in Sec. II. Subsequently, the simulation parameters and results are presented in Sec. III. Finally, a summary and discussion are stated in Sec. IV.

II. SYSTEM MODEL

Based on the system-level approach, the separate resource allocation for a LTE homogeneous network in DL transmissions can be examined. The pre-generated data such as large-scale fading are discussed. The CC selection, RB scheduling and UE throughput calculation used in this work are described as well.

A. Pre-Generated Data

According to [10], a hexagonal grid of 19 sites with three sectors each is selected to model such a homogeneous network. First of all, antenna gain and pathloss are generated in connection with this network layout. The eNB antenna pattern for each sector (in dB) is given by

$$A_{\mathrm{H}}(\theta) = -\min\left[12\left(\frac{\theta}{65^\circ}\right)^2, 15\mathrm{dB}\right], \tag{1}$$

where $-180^\circ \leq \theta \leq 180^\circ$. The pathloss model (in dB) is defined as

$$\begin{aligned} L(R) = 40(1 - 4\cdot 10^{-3}\cdot \mathrm{Dhb})\cdot \log_{10}(R) - 18\log_{10}(\mathrm{Dhb}) \\ + 21\log_{10}(f) + 80\mathrm{dB}, \end{aligned} \tag{2}$$

where R is the eNB-UE separation distance (in km). Let f and Dhb be the carrier frequency (in MHz) and the eNB antenna height above the average rooftop level (in m), respectively. The antenna height of 15 metres is applied to (2). In this way, the large-scale fading map formed by both antenna gain and pathloss for a specific sector on different CCs can be generated. For instance, Fig. 1 shows the network layout resulting in the pathloss map of a CC in Fig. 2.

Another is the spatially correlated shadow fading based on [11]. A single shadowing map per site on a CC is generated as illustrated in Fig. 3. Note that only the pathloss and shadow fading of CC#3 on 3.4 GHz band are displayed. Similar results were produced by the same method for other bands, in particular 2.1 GHz.

Finally, the wideband signal-to-interference-plus-noise ratio (SINR) map including antenna gain, pathloss and shadowing for CC#3 is obtained in Fig. 4. This exists for every CC in every band.

A constant number of UEs per sector is randomly dropped within the network layout. Due to the known strongest signal on each point within the SINR map, the serving sector can be identified for each UE. For small-scale fading, the method of correlated fading generation in [12] is used for each CC.

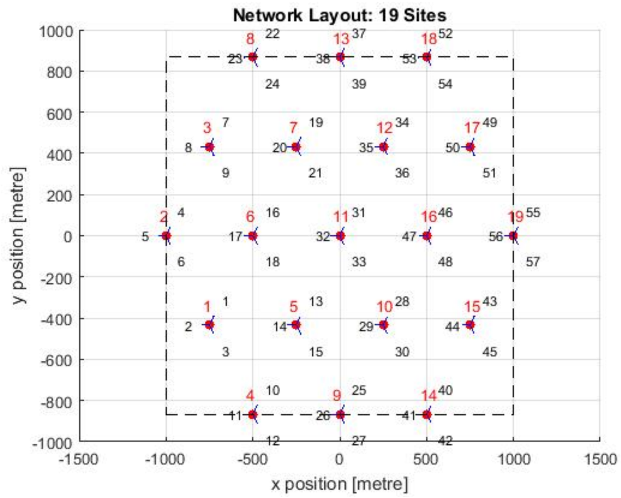

Fig. 1. The tri-sectorised hexagonal cell layout.

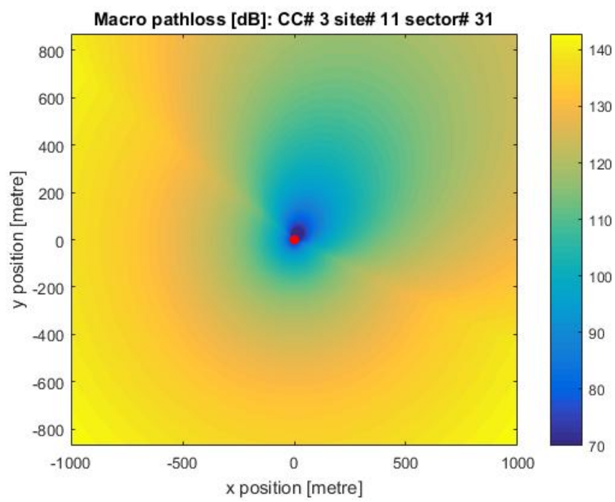

Fig. 2. Pathloss and antenna gain map (in dB).

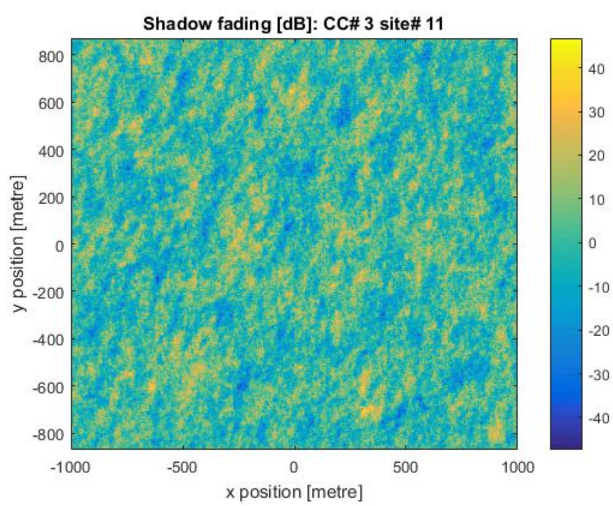

Fig. 3. Shadowing loss map (in dB).

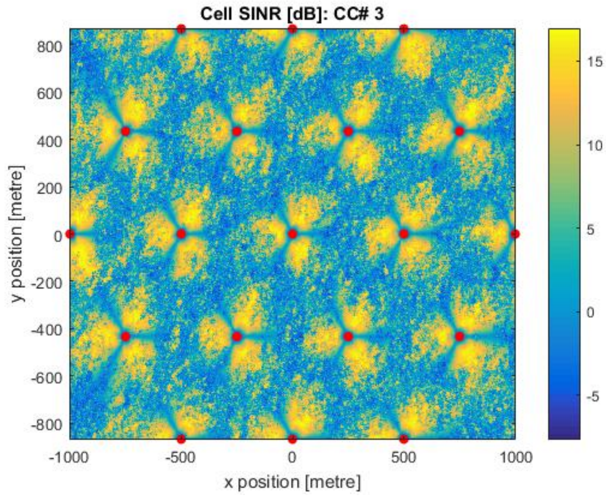

Fig. 4. Wideband SINR map (in dB).

B. CA Capability and Selection

The intra- and inter-band non-contiguous CA can be modelled. In this paper 4 CCs with 5 MHz bandwidth each from either the same or different combination of frequency bands (900, 1800, 2100 and 3400 MHz) operating on each sector are considered.

Although the eNB offers 4 CCs from either a single or dual bands, the number of supported CCs per UE is limited by UE CA capability. There are two UE types: LTE (Rel-8) and LTE-A (Rel-10) UEs. At each subframe, a LTE UE is able to access only a single CC while 2 CCs can be utilised simultaneously by a LTE-A UE[2]. Also, a number of LTE-A UEs is probably adjusted in this simulation.

The CC selection could be via random, RR or RSRP-based approaches, performed every subframe. This means that the allocated CC (CC#1, CC#2, CC#3 and CC#4) for UEs may be changed at each 1-ms transmission time interval (TTI). For example, if the RSRP method is used, the CC(s) with maximum RSRP is assigned to UE i as follows [2]

$$c^* = \arg\max_{c \in C} \mathrm{rsrp}_c^i, \tag{3}$$

where C is the set of available CCs per sector. Let rsrp_c^i be the RSRP of UE i on CC c. Note that the maximum RSRP is determined resulting from the wideband SINR map.

C. RB Scheduling

After the CC selection, RB(s) will be assigned to a specific UE on each CC. The RR scheduler could be viewed as a benchmark while other scheduling techniques such as best-CQI and PF may be deployed as well. For instance, the PF scheduler with CA can be implemented [2]

$$i^* = \arg\max_{i \in U_c} \frac{r_{c,k}^i(t)}{R^i(t)}. \tag{4}$$

[2]Assume that both LTE and LTE-A UEs are the dual band device.

At each subframe t, $RB_{c,k}$ will be scheduled to the UE i with maximum UE utility function. Let $RB_{c,k}$ and U_c be the RB k and the set of UEs on CC c, respectively. The achievable data rate $r_{c,k}^i(t)$ of UE i on $RB_{c,k}$ defined in [7] is used. Furthermore, $R^i(t)$ being the average data rate of UE i at time t is then expressed

$$R^i(t) = \left(1 - \frac{1}{t_c}\right) R^i(t-1) + \frac{1}{t_c} \sum_{c \in C_i} T_c^i(t-1). \tag{5}$$

Denote the average window size and the set of allocated CCs for UE i by t_c and C_i, respectively. $T_c^i(t-1)$ is the actual data rate (throughput) of UE i on CC c at time $(t-1)$.

D. UE Throughput

After the simulation is terminated, the average throughput of a given UE (in Mbps) can be computed [3]

$$T_{\text{avg}} = \frac{B_{\text{total}}}{N_{\text{TTI}} \cdot L_{\text{TTI}} \cdot 10^6}, \tag{6}$$

where the total bit $B_{\text{total}} = \sum_{i \in A} \sum_{c \in C} (\mathrm{ACK}_{i,c} \cdot \mathrm{TB}_{i,c})$. Let $\mathrm{ACK}_{i,c}$ and $\mathrm{TB}_{i,c}$ be the acknowledgment and the transport block size (in bits) at TTI i and on CC c, respectively. Denote the set of accounted TTIs and available CCs by A and C, respectively. N_{TTI} is the number of accounted TTIs while the TTI length (L_{TTI}) of 1 ms is used.

III. Performance Evaluation

The separate CC selection and RB scheduling as discussed in Sec. II is evaluated in terms of UE throughput. The simulation is performed and results are presented by means of MATLAB.

A. Simulation Parameters

Tab. I shows the simulation parameters. Note that only UEs within the coverage area of the central site are considered in this simulation (the adjacent sites are sources of downlink interference).

TABLE I
Simulation Parameters

Parameter	Assumption
Cellular layout	Hexagonal grid of 19 sites
Inter-site distance	500 m
Path loss model	As mentioned in Sec. II
Lognormal shadow fading	$L_s \sim N(\mu, \sigma^2)$
Antenna pattern (horizontal)	As mentioned in Sec. II
Number of CCs	4 CCs per sector
Carrier frequency	942.5, 1842.5, 2140 and 3505 MHz
System bandwidth	5 MHz per CC
Channel model	ITU Pedestrian A model
UE speed	5 km/h
Number of UEs	10 UEs per sector (50% LTE-A UEs)
Total BS TX power (P_{total})	43 dBm
CC selection	RR, random and RSRP
Scheduling	RR, best-CQI and PF
Transmission mode	Single-input single-output (SISO)
Simulation length	50 TTIs

B. UE Throughput Distribution

The empirical cumulative distribution function (ecdf) of average UE throughput from (6) is determined for the performance evaluation. First, the impact of CA types and CC selection is investigated. The comparison of UE throughput distribution between the intra- (4 CCs on 2100 MHz) and inter-band non-contiguous CA (2 CCs on 2100 MHz and 2 CCs on 3400 MHz) under different CC selection and RR scheduling is presented in Fig. 5.

For both intra- and inter-band CA, the mean and peak UE throughputs were significantly enhanced by the random and RR selection. For example, the peak throughputs (the 95% point of the UE throughput ecdf) of the RR approach (green solid and magenta dashed lines) were around three times as large as the RSRP one (blue solid and black dashed lines). However, it appeared to be the small deviation of edge throughputs (the 5% point of the UE throughput ecdf) from all scenarios.

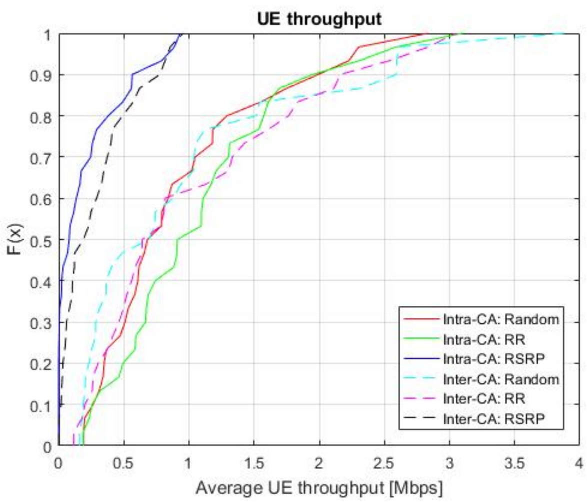

Fig. 5. The ecdf of UE throughput under different CA types and CC selection.

Furthermore, Fig. 6 shows the average number of assigned CCs per site per subframe[3] corresponding with the six combination of CA types as listed in Tab. II.

TABLE II
CA SCENARIOS

Type	CA scenarios
1	Intra-band CA with random selection
2	Intra-band CA with RR selection
3	Intra-band CA with RSRP selection
4	Inter-band CA with random selection
5	Inter-band CA with RR selection
6	Inter-band CA with RSRP selection

By using the random and RR manners, the load balance across different CCs (CC#1, CC#2, CC#3 and CC#4) could be obtained. However, a CC with better channel condition

[3]There are 45 CCs in total resulting from 15 LTE UEs (15 $\times$ 1 CC) and 15 LTE-A UEs (15 $\times$ 2 CCs) in this simulation.

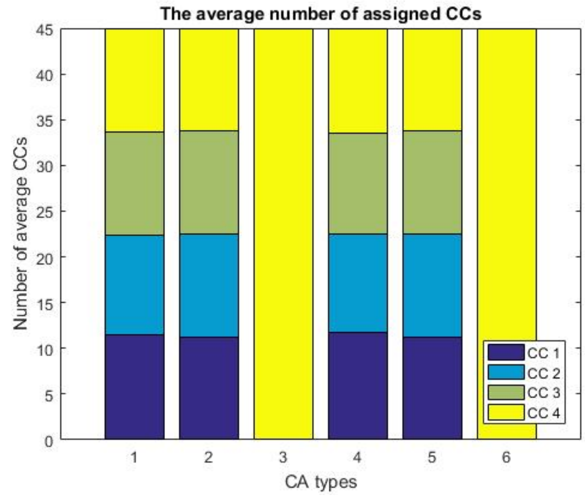

Fig. 6. The average number of assigned CCs.

(CC#4) was always selected by the RSRP approach. This led to not only undesirable load imbalance but also degraded UE throughputs.

Second, the effect of different frequency bands is analysed as illustrated in Fig. 7. The band of the first two CCs is 2100 MHz while the remaining two CCs may use either 900, 1800 or 3400 MHz. The RR scheduler and CC selection including RR and RSRP are used in this scenario.

According to the results, there are similar trends of UE throughput distribution under different combinations of bands. This resulted in the little variation of UE throughput (mean, edge and peak) values for both RR and RSRP selection.

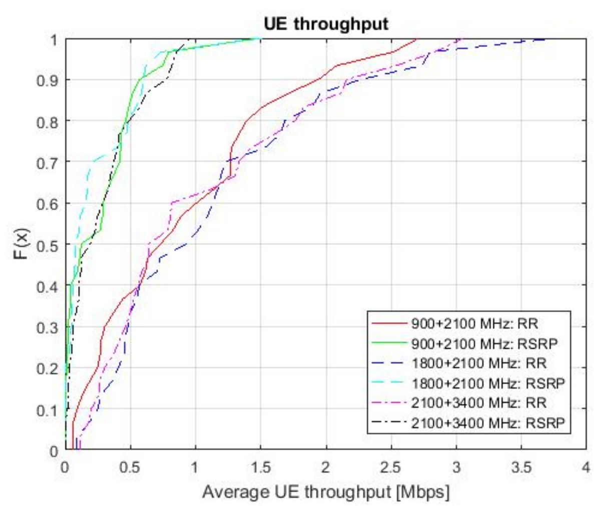

Fig. 7. The ecdf of UE throughput under different frequency bands.

Third, the choice of scheduling techniques including RR, best-CQI and PF is evaluated in Fig. 8. The inter-band CA on 2100 and 3400 MHz with RR and RSRP selection is modelled.

For both CC selection, the best-CQI scheduler (green solid and magenta dashed lines) outperformed other scheduling techniques in terms of mean and peak throughputs. The edge throughput seemed to be very low for all cases. Although the higher throughput could not be obtained, there was an increase of UE throughput fairness[4] by means of RR and PF scheduling.

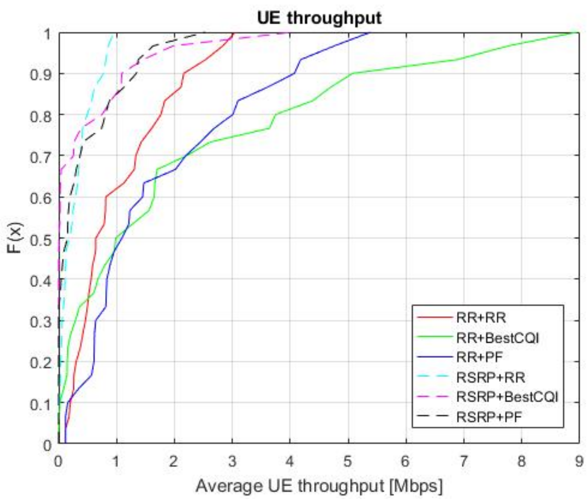

Fig. 8. The ecdf of UE throughput under different scheduling approaches.

In summary, for all scenarios of CA implementation types and frequency bands, the load balance across CCs from CC selection is first required. In addition, the choice of RB scheduling should be considered in connection with throughput, fairness and complexity.

For instance, RR component carrier selection and best-CQI scheduling appeared to be the best match to offer the highest UE throughputs (mean and peak) as shown Fig. 8. Although the load across CCs could be balanced by RR selection, there was the cost of fairness from the best-CQI scheduler. To improve the fairness, the simplest RR scheduling could be performed but lower throughputs were obtained. To compromise between throughput and fairness, the PF scheduler is a good choice. However, there is higher complexity as compared to the RR scheduling.

IV. Discussion and Conclusions

The separate resource allocation with CA including CC selection and RB scheduling for a LTE cellular network in DL transmissions was modelled by system-level simulation. The UE throughput being the performance metric was evaluated under various CA types, frequency bands, CC selection and scheduling techniques.

According to the results, either random or RR approach could be selected to balance the load across CCs while the best-CQI scheduler seemed to be the first choice to boost the UE throughput. However, there is a trade-off between the UE performance and computational complexity that should be considered when using the CC selection and RB scheduling. This results in alternative RR and PF schedulers.

Regarding open challenges, one should consider how the CC load balance can be enhanced, in particular the RSRP selection. Another challenge is how the resource allocation with CA is modelled in connection with the theoretical work, small cell deployments and unlicensed LTE.

[4] According to [13], the fairness index is defined to measure the equality of resource (throughput) distribution over multiple users. This index is restricted between [0,1]. 0 refers to the total unfairness, whereas 1 means the total fairness of throughput distribution.

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